Scientific linkage and technological innovation capabilities: international comparisons of patenting in the solar energy industry

Xia Fan[1] · Wenjie Liu[1] · Guilong Zhu[1]

Abstract From the perspective of science-based innovation, this study introduces measures of both scientific linkage (technology-science correlation index) and technological innovation capabilities (relative growth rate, relative patent position and revealed technological advantage) to compare and analyze the international competitiveness of solar energy technologies among the United States, the European Union, Japan, China and South Korea, based on the solar energy technologies-related patents in the European Patent Office Worldwide Patent Statistical Database. After making international comparisons of their technological development and innovation paradigm, we find that there are different innovation characteristics of various technology fields within the solar energy industry and then propose some relevant policy recommendations for latecomers to implement catch-up strategies. The results show that the leading countries and regions of the solar energy industry such as the United States and the European Union focus mainly on science-based innovation, while Japan and latecomers like China and South Korea pay more attention on technology-based innovation. In addition, those two fields within the solar energy industry present opposite innovation characteristics: solar photovoltaic technologies, especially thin film and organic cells, present strong technological innovation capabilities with high scientific linkage, while solar thermal technologies show strong technological innovation capabilities with low scientific linkage.

Keyword Science-based innovation · Scientific linkage · Technological innovation abilities · Solar energy technologies · Catch-up

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Introduction

With the depletion of the world's oil reserves and the growing disruption of our climate, the development of clean, renewable sources of energy, particularly solar energy, is the growth industry of the 21st century (Weiss et al. 2009; Luan et al. 2013). Whether a country is at the forefront of energy technologies and leads the next energy revolution determines the future of the national economy to a large extent, including the potential for economic growth, long-term energy security and the global leadership in the fields of economic development and technological innovation (Sorensen 2000; Hoppmann et al. 2013; Motohashi and Tomozawa 2014).

Over the years, it is difficult for China, South Korea and other latecomer countries to catch up with the United States, the European Union, Japan and other developed counterparts in renewable energy industry, while the development of this science-based industry needs immediate attention and technological innovation (Zhang et al. 2015). In Europe, rapid expansion of renewable power generation, particularly solar, has occurred in recent years, driven by the requirements of the European Union's Renewable Energy Directive and national targets. In the United States, the market for renewables has been growing strongly, in large part due to the continuation of stimulus policies directed at renewable energy (Birol 2013). Asian market led by Japan, China and South Korea has experienced phenomenal growth in recent years due to both technological improvements resulting in cost reductions and government policies supportive of renewable energy development and utilization (Timilsina et al. 2012). According to the latest report from the International Energy Agency (IEA), almost two-thirds of the increase in power generation from renewables is in non-OECD countries over the outlook period to 2035. The increase in China is more than that in the European Union, United States and Japan combined (Birol 2013).

Today, no area, in terms of renewables, holds more promise than the investments and innovation in solar energy technologies. Due to differences in the innovation trajectory between the solar energy industry and traditional industries, the contribution of scientific research in science-based innovation paradigm differs largely from that in traditional paradigm so that scientific linkage and technological innovation capabilities present a certain regularity, which provides latecomer countries with opportunities to implement strategies to catch up with their leading counterparts.

Though the research of solar energy has a long history, it has not been seen as a priority area of research until more recently (Hassan et al. 2014). The characteristics of science-based innovation in the solar energy industry and the corresponding contribution to technological innovation have been identified (e.g., Hara et al. 2003; Tomozawa 2013; Motohashi and Tomozawa 2014). On the one hand, indirect knowledge flow through publications and patents is relevant in "science-based regimes", where the nature of scientific knowledge is basic (Freeman and Soete 1997; Gilsing et al. 2011). In science-based industries, the innovation system are easily influenced by exogenous variables due to the importance of the role of the science sectors, such as universities and public research institutions rather than existing technologies (Nelson and Winter 1982). It is found from many concrete examples that these industries are usually of high scientific linkage, as there is a strong relationship between science and industrial innovation. The growth of science-based industries such as biotechnology, new materials, electronic information and renewable energy emerge from fundamental scientific discoveries and techniques (Cardinal et al. 2001), which are constantly involving and even epoch-making. Consequently, these

scientific discoveries are characterized with exogeneity, discreteness and quasi-randomness (Cohen et al. 2000) and corresponding innovation processes are of linearity (Gambardella 1995). Due to the low similarity of knowledge topics with low relatedness (Granovetter 1973), knowledge exchange opportunities are provided to produce ideas collision and innovative spark (Jerome 2013), which is helpful to stimulate innovation in different scientific backgrounds and areas.

On the other hand, direct interactions among firms are important for "technology-based regimes", based on more applied knowledge created within enterprises (Böhme et al. 1978; Gilsing et al. 2011). But there is not strong interaction between technology and scientific research in technology-based innovation. This regime will require no technological miracles or social engineering-only the systematic application of many available, straightforward techniques. The technological development of those enterprises in traditional industry depends heavily on their existing technological capabilities rather than on exogenous variables (Nelson and Winter 1982). This is because scientific principles are mature and kept basically unchanged in technology-based industries such as household appliances, traditional automobile and manufacturing, where innovation activities are dominated by endogenous and accumulated technological progress. Content transferred among such knowledge may also represent homogenous and unuseful information. Thus, the potential of the creative convergence in scientific performance could be largely exhausted (Kim and Kogut 1996). Scientific relatedness in solar energy even has a negative relationship with scientific output (Zhang et al. 2015). But accumulated technological knowledge in both sources and thereby the number of references that are required for from new applicants grows constantly in a life cycle (Haupt et al. 2007).

Although the above studies reflect the innovation paradigm of the global solar energy industry to some extent, related issues should be expanded from one-dimensional single-level to multi-dimensional and multi-level mining. This study thus has three primary research questions: (1) at the national level, what different innovation characteristics are presented in the solar energy industry of leading countries and latecomers? (2) at the technological field level, given various ones of the solar energy industry can be classified either science-based or technology-based, what regularity scientific linkage and technological innovation capabilities are characterized with? and (3) at the technological sub-field level, how do these results show in the light of technological life cycles?

The scope of our study covers five countries and regions, comprising of the United States, the European Union, Japan, China and South Korea due to their overwhelming patent applications registered in the European Patent Office (EPO) Worldwide Patent Statistical Database. To analyze the international level of solar energy technologies in major countries and regions, we introduce measures of both scientific linkage [technology-science correlation index (TSCI)] and technological innovation capabilities [relative growth rate (RGR), relative patent position (RPP) and revealed technological advantage (RTA)] to investigate the solar energy technologies relevant patents granted to the United States, the European Union, Japan, China and South Korea. After making international comparisons of their technological development and international competitiveness, we find different innovation characteristics of various technology fields within the solar energy industry and then propose some relevant policy recommendations for latecomers to implement catch-up strategies.

The paper is organized as follows: The measures and methodology used in the study are described in section "Measures and methodology". This is followed by section "Data and summary statistics" data and summary statistics. Section "International comparative studies" assesses the empirical results using a comparative analysis of scientific linkage

and technological innovation capabilities. After these discussion, section "Robustness checks" is a sub-field analysis that serves as robustness checks. Finally, key conclusions are drawn in section "Conclusions and suggestions".

Measures and methodology

Scientific linkage

Patent analysis is an effective approach to study the issue, as the patent citation information system links industrial development with related scientific fields (e.g., Collins and Wyatt 1988; Meyer 2000; Michel and Bettels 2001; Shibata et al. 2010; No et al. 2015). It is not uncommon for patent applicants or examiners to cite other literature. Cited literature can be divided into two categories: one is other patents, and the other is non-patent literature (NPL) (Brusoni et al. 2005). The latter, namely the scientific literature, includes journal articles, conference papers, dissertations, research disclosure, technical reports, academic books, etc.

The degree of scientific linkage can be measured by NPL (e.g., Meyer 2000; Glänzel and Meyer 2003; Motohashi and Tomozawa 2014). The reasons for patents to cite scientific literature as prior arts are various (Schmoch 1993), nevertheless, it is a critical indicator of the quality of knowledge for building internalization capability, and is particularly essential for the technology latecomers (Hu and Mathews 2008). A high level of scientific linkage thus indicates that a patent is building on a technology base that is grounded in advances in science (Wu and Mathews 2012). In this research, scientific linkage which assesses the dependence of scientific research in a certain industry is defined as:

$$\frac{P_{\mathrm{NPL}}}{P_{\mathrm{total}}}$$

where P_{NPL} refers to the count of patents citing non-patent literature (NPL), and P_{total} refers to the count of total patents. This means that the denominator represents the industrial development, and the numerator indicates the degree of association between industrial development and related scientific research.

The industry-science correlation index (ISCI) employs mathematical transformation to transform this indicator into another value, ranging from -100 to 100—as introduced by Zhang and Lei (2015). This formula standardizes the scientific linkage of various industries, which uses a uniform standard to describe the differences of scientific linkage among different industries. A notion of technology-science correlation index (TSCI) similar to that of Zhang and Lei (2015) is used in our study, where specific technology portfolios within the industry are taken into account. Taking zero value as a criterion, each technology portfolios can be classified as either science-based (above zero) or technology-based (below zero) in terms of scientific linkage. At the same time, the greater the positive value is, the stronger the tendency of science-based innovation is; the greater the absolute value of negative one is, the stronger the tendency of technology-based innovation is.

$$\mathrm{TSCI}_{ij} = 100\,\mathrm{Sgn}\left(\frac{P_{\mathrm{NPL},j}}{P_{\mathrm{total},j}} - \frac{\sum_i \frac{P_{\mathrm{NPL},i}}{P_{\mathrm{total},i}}}{i}\right)\sqrt{\left(\frac{P_{\mathrm{NPL},j}}{P_{\mathrm{total},j}} - \frac{\sum_i \frac{P_{\mathrm{NPL},i}}{P_{\mathrm{total},i}}}{i}\right) * \mathrm{Sgn}\left(\frac{P_{\mathrm{NPL},j}}{P_{\mathrm{total},j}} - \frac{\sum_i \frac{P_{\mathrm{NPL},i}}{P_{\mathrm{total},i}}}{i}\right)}$$

where P_{NPL} refers to the count of patents citing Non-Patent-Literature (NPL), P_{total} refers to the count of total patents, i refers to country i and j refers to technology portfolio j.

Technological innovation capabilities

In order to measure technological innovation capabilities, we further learn from the indicators adopted by researchers such as Soete ([1987](#)), Grupp ([1994](#)), Ernst ([1998](#)), Brockhoff et al. ([1999](#)), Meyer ([2006](#)), Frietsch and Schmoch ([2010](#)), Wu and Mathews ([2012](#)), Jang et al. ([2013](#)) and Wu ([2014](#)) to evaluate technology portfolios.[1] Although various indicators are employed by these researchers, the three indicators (namely RGR, RPP and RTA) are widely recognized due to their importance to evaluate the level of technological innovation capabilities. It also should be noted that the contents of these measures are emphasized differently: RGR focuses on technological attractiveness, and RPP and RTA represent R&D scale and R&D efficiency respectively. Definitions of the indicators are described in the following subsections.

Relative growth rate (RGR)

Technology attractiveness is measured by relative growth rate (RGR) which refers to the average growth rate of patents granted for a particular technology portfolio relative to the average growth rate of total patents granted for all the technology portfolios over the total period of analysis (Brockhoff et al. [1999](#)). The higher RGR in a specific technology portfolio indicates the higher level of technological attractiveness for this specific technology portfolio in the industry.

$$\text{RGR}_j = \frac{G_j}{G_{\text{Total}}}$$

where G_j refers to the average growth rate of patents granted for the technology portfolio j and G_{Total} refers to the average growth rate of total patents granted for all the technology portfolios.

Relative patent position (RPP)

Ernst ([1998](#)) applied relative patent position (RPP) to illustrate the scale and intensity of the innovation of a specified industry in a certain country. This study refers the RPP of a country in a particular technology portfolio to measure the number of patents owned by the country relative to the number of patents of the most active competitor country in that particular technology portfolio. That is, here the most prolific patentee in the sample pool is acted as a benchmark, with the maximum value of the RPP in each technology portfolio being unity. RPP is defined in the present paper as:

$$\text{RPP}_{ij} = \frac{P_{ij}}{\max_i P_{ij}}$$

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[1] Brockhoff ([1992](#)) first introduced the concept of technology portfolios and used patent data to evaluate them. Thereafter, researchers such as Chen ([2011](#)), Schmoch ([1995](#)), Ernst ([1995](#)) and NBER (National Bureau of Economic Research) scholars then followed and demonstrated the viability of various indicators. Even though their targets are different, it is widely recognized that technology portfolios measured by patent data contain useful information to estimate a nation's technological innovation capacity [e.g. Hu ([2012](#)); Wu and Mathews ([2012](#))].

where P_{ij} refers to the number of granted patents for the technology portfolio j in country i.

Revealed technological advantage (RTA)

RTA has been proposed by Soete (1987) as a measure of technological specialization, analogous to the concept of Revealed Comparative Advantage (RCA) originally applied in the context of international trade specialization (Balassa 1965). A number of studies have applied RTA in the comparison of country-level technological innovation capabilities (e.g. Schmoch and Schnöring 1994; Pavitt and Patel 1988; Meyer 2006; Frietsch and Schmoch 2010). RTA of a region in a particular technological field is provided by the region's share of global patenting in that field, divided by its share of global patenting in all technology portfolios. The higher the value of RTA in a certain technology portfolio for a country, the more that the country produces a higher level of technological specialization. This study adopts RTA to measure the relative strength of different technological portfolios for each country, and is thus able to represent the relative technological efficiency of a country in relation to the specific technology portfolio. RTA is defined in the present paper as:

$$\text{RTA}_{ij} = \frac{\text{PS}_{ij}}{\text{PS}_i} = \frac{P_{ij}/\sum_i P_{ij}}{\sum_j P_{ij}/\sum_{ij} P_{ij}}$$

where P_{ij} refers to the number of granted patents for the technology portfolio j in country i.

Data and summary statistics

Data

Data in this study are retrieved from Global Patent Index (GPI), also known as one of the European Patent Office (EPO) Worldwide Patent Statistical Database. It contains more than 20 tables with bibliographic data, citations and family links of 90 million applications of more than 80 countries. GPI is a cumulative database updated every Friday at 12.00 h CET.

It is adopted that the definition of solar energy technology by using International Patent Classification (IPC) provided by World Intellectual Property Organization (WIPO 2014), as defined in "Appendix ". The correspondence between IPC symbols and technology fields is not always clear-cut. Therefore, it is difficult to capture all patents in a specific technology field. Nonetheless, the IPC-based definitions of the technology presented above are likely to capture the vast majority of related patents. The data was retrieved and downloaded during November 1–30, 2015. As the patent applications saw a rise in the oil shock era from 1973 to the early 1980s, we take the year of 1973 as the starting year of the study. There are 500,077 solar energy patent filings over the period of 1973–2014.

According to WIPO's guide, the highest level of hierarchy of the IPC, namely section, represents the whole body of knowledge which may be regarded as proper to the field of patents for invention, divided into eight sections.[2] In terms of sections, the 36 solar energy

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[2] The IPC is a hierarchical classification system. The contents of lower hierarchical levels are subdivisions of the contents of the higher hierarchical levels to which the lower levels are subordinated. The Classification separates the whole body of technical knowledge using the hierarchical levels, i.e., section, class, subclass, group and subgroup, in descending order of hierarchy.

technology related IPCs are then classified into four technology portfolios and two corresponding technology fields[3] in this paper, see Table 1.

Summary statistics

Global statistics

The growing trend of patent filings in solar energy industry worldwide is demonstrated in Fig. 1. Glancing at the figure, the exponential growth in the global solar energy industry stands out ($y = 1E - 57e^{0.0703x}$, $R^2 = 0.8527$). All the patent filings can be divided into four stages (see Fig. 1): (1) due to the oil shock era from 1973 to the early 1980s (the first oil shock occurred in 1973 and the second one in 1979), patent applications experienced a marked rise, standing at 6781 in the year 1982; (2) in the second stage, patent applications kept basically unchanged and the number of patent applications each year over this period was around 5000; (3) because of sustained policy support and rising oil price, solar energy markets have regained momentum since early 2000, exhibiting phenomenal growth recently (Timilsina et al. 2012), reaching just over 20,000 in 2005; (4) in the final stage, patent counts showed a high speed growth in the wake of the enlarging scale of industrialization of solar energy technologies after 2006. Given that ending statistical decline is due to some patent applications published lagged, it is clear that the number of patents saw a continuous upward trend throughout the period 1973–2014.

Figure 2 clearly displays the global patent distribution and helps us to conduct the following analysis. Although most countries and regions have developed their solar energy industry by 2014, patents related to solar energy technologies were applied mainly by the United States, the European Union, Japan, China and South Korea. Among leading countries, the number of patents granted to the United States and the European Union was 73,886 and 33,780 respectively, while that of Japan was highest, reaching 169,392 during the period. As latecomers in the global solar industry, both China and South Korea also took up a large portion of patents, with the number of patents 80,011 and 39,399 respectively.

Considering that there has been few publications and patents as well as no systematic study of the solar energy technologies until the mid-1980s in China, the following international comparative study takes the year 1985 as the beginning point so that the following comparative analysis of these five countries and regions is reasonable and valid. Using structured retrieval provided by EPO GPI retrieval system, we select 360,225 patent data of the United States, the European Union, Japan, China and South Korea from January 1, 1985 to December 31, 2014 as data samples for international comparisons of the next section.

Country statistics

Figure 3 presents that the number of solar energy technologies related patents was granted to the United States, the European Union, Japan, China and South Korea between 1985 and

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[3] Solar energy technologies can be broadly classified along the following continuum: (1) photovoltaics (PV); (2) solar thermal (Timilsina et al. 2012). The PV technology converts radiant energy contained in light quanta into electrical energy when light falls upon a semiconductor material, causing electron excitation and strongly enhancing conductivity (Sorensen 2000). Solar thermal technology uses solar heat, which can be used directly for either thermal or heating application or electricity generation.

Table 1 Solar energy technology portfolios related IPCs

Energy-related technology	Technological field	Technological portfolio	Description
Solar energy	Solar thermal	TP E	Fixed constructions, including 2 IPCs
		TP F	Mechanical engineering; lighting; heating; weapons; blasting, including 21 IPCs
	Photovoltaics (PV)	TP G	Physics, including 3 IPCs
		TP H	Electricity, including 10 IPCs

Specific IPCs defined in "Appendix "
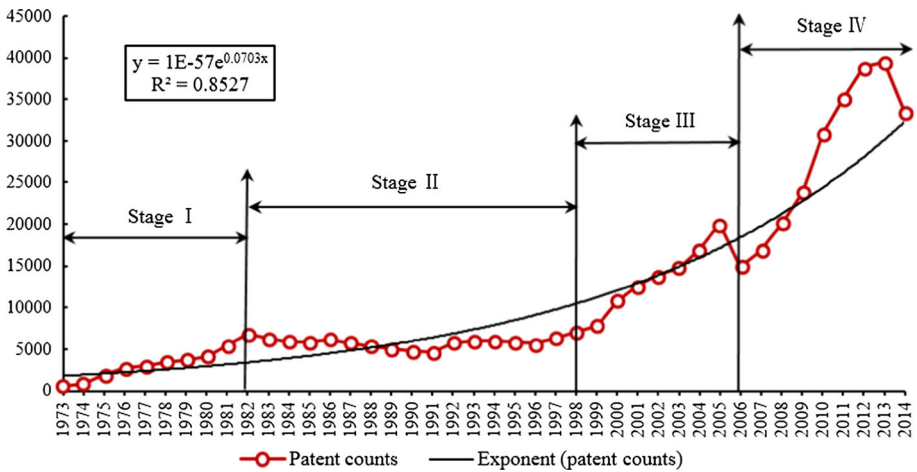
Fig. 1 Annual patents granted in the global solar energy industry, 1973–2014. *Note* ending statistical decline is due to some patent applications published lagged. *Source* EPO and compiled by the authors

2014. Patent counts of the five countries and regions kept basically unchanged from 1985 to 1996, remaining at around 5000. But since the mid-1990s, China, the United States, the European Union, South Korea's solar energy technologies-related patents have experienced a marked rise while Japan showed a downward trend alone.

As shown in Table 2, patents granted to technology portfolios E, G and H of the solar industry in Japan were more than the figures for other countries and regions, accounting for 29.48, 37.18 and 33.54% of the global total respectively. In addition, China, which had the largest proportion (38.60%), applied for 26,529 patents of technology portfolio F while patents of that applied by South Korea was minimal (1837), accounting for only 2.67% of the total. Though the number of patents reflect the R&D investment on a certain technology portfolio of a country to some extent, it is difficult to reveal its innovation mechanism within the industry as well as the role of different factors in developing the industry only in terms of patent counts.
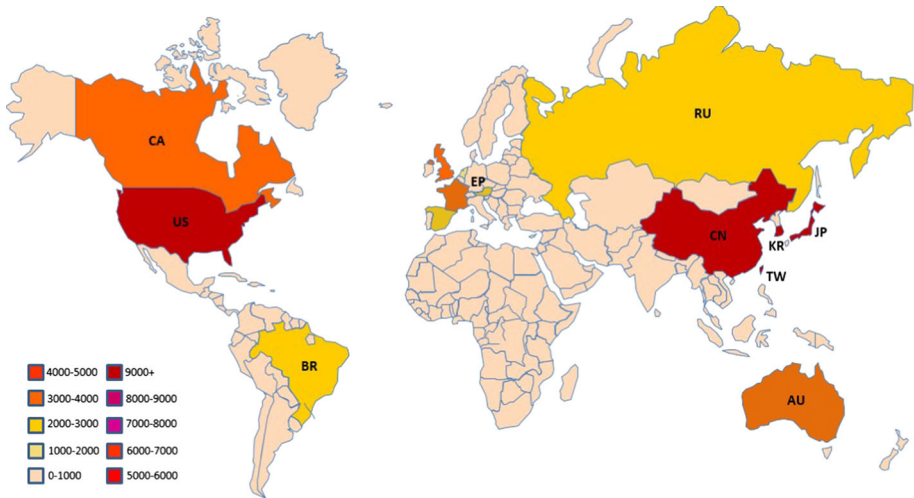
Fig. 2 The global patent map of solar energy technologies, 1973–2014. *Source* EPO and compiled by the authors
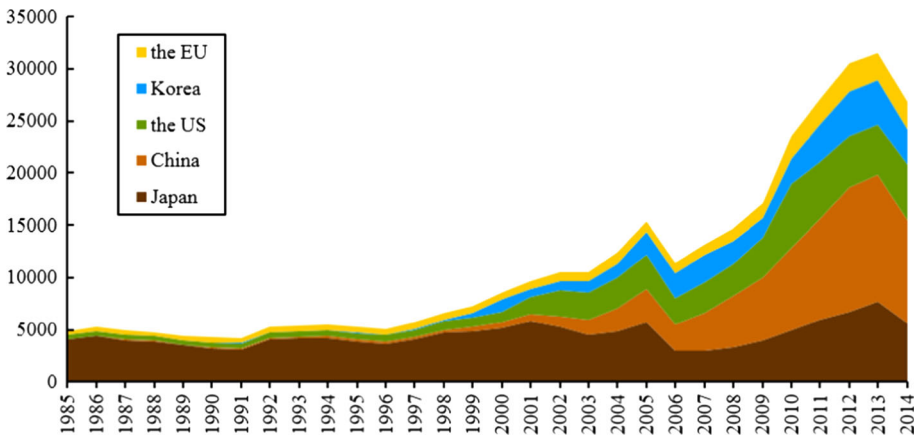

Fig. 3 Annual solar energy technologies-related patents granted to the United States, the European Union, Japan, China and South Korea, 1985–2014. *Source* EPO and compiled by the authors

International comparative studies

A comparative analysis of scientific linkage

While the number of patent application in solar industry shows periods of up and down, the number of scientific publications has increased sharply after the 1990s, suggesting that scientific research did not lose its momentum even in the recent period (Tomozawa 2013). We further searched the number of patents citing NPL and scientific linkage index of the United States, the European Union, Japan, China and South Korea, finding that having a large number of patents does not mean that the country's solar energy industry is more science-based, while a small number of patents also does not represent that the country's

Table 2 Solar energy technologies-related patents granted to the four technology portfolios in the United States, the European Union, Japan, China and South Korea, 1985–2014. *Source* EPO and compiled by the authors

Region	TP E		TP F		TP G		TP H	
	Patent counts	Share %	Patent counts	Share %	Patent counts	Share %	Patent counts	Share %
The US	1087	5.84	3665	5.33	11,121	16.43	53,808	17.51
The EU	535	2.87	2785	4.05	1505	2.22	25,283	8.23
Japan	5489	29.48	6963	10.13	25,167	37.18	103,043	33.54
China	2445	13.13	26,529	38.60	3899	5.76	45,583	14.84
Korea	246	1.32	1837	2.67	12,861	19.00	24,274	7.90
Total	9802	52.64	41,779	60.78	54,553	80.60	251,991	82.01
Global total	18,622	100.00	68,733	100.00	67,685	100.00	307,261	100.00

solar energy industry focuses on technology-based innovation. Figure 4 compares the scientific linkage among the United States, the European Union, Japan, China and South Korea between 1985 and 2014. On the one hand, the United States and the European Union's solar industries were typical science-based industries. The United States had 20,437 NPL patents with scientific linkage of 0.277 on average, which fluctuated between 0.2 and 0.6 over the period, showing an S-shaped curve in line with the evolution of science-based industries. In contrast, the European Union had only 8863 NPL patents and
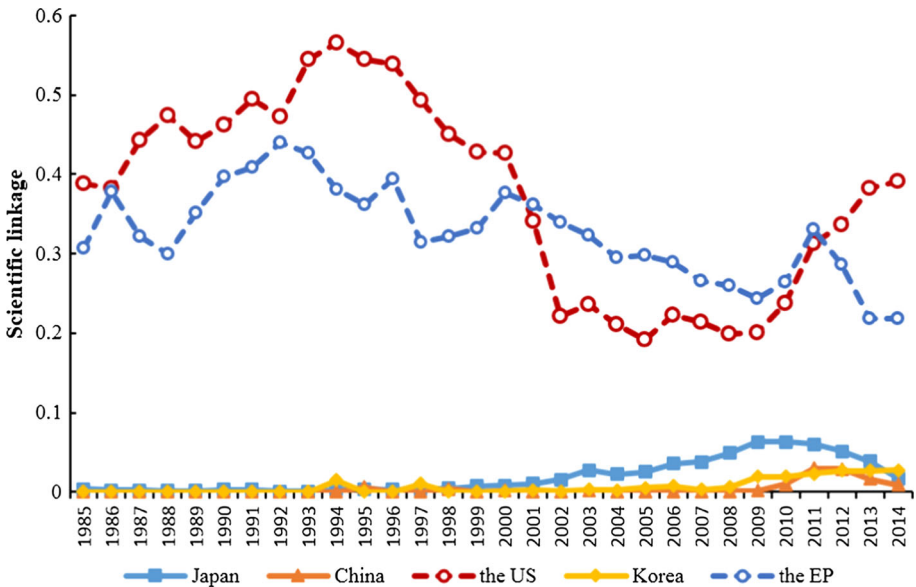

Fig. 4 Comparisons of scientific linkage among the United States, the European Union, Japan, China and South Korea, 1985–2014. *Source* EPO and compiled by the authors

its scientific linkage was 0.262 on average, which experienced some slight fluctuations throughout the period (around 0.3). It is clear that solar energy technologies of both the United States and the European Union were progressed by the active participation of the science sector such as universities and public research intuitions. On the other hand, the figures for Japan, China and South Korea was 2932, 751 and 537 respectively and their scientific linkage was minimal (0.017, 0.009 and 0.014 on average respectively), though it did not show a slight upward trend until more recently. The solar energy industry of Japan that had the largest proportions of patents paid more attention to technology-based innovations, latecomer countries China and South Korea as well.

A comparative analysis of technological innovation capabilities

As shown in Table 3, these five countries and regions had different technological innovation capabilities in technology portfolios E, F, G and H. The innovation strategies adopted by the United States and China were at opposite poles. In the United States, technology portfolios H and G were characterized by higher RPP and RTA (representing the R&D scale and R&D efficiency respectively), which means that its photovoltaic

Table 3 Technological innovation capabilities of the four technology portfolios in the United States, the European Union, Japan, China and South Korea, 1985–2014. *Source* EPO and compiled by the authors

Technology portfolios	Technological innovation capabilities		
	Relative growth rate (RGR)	Relative patent position (RPP)	Revealed technological advantage (RTA)
US/E	1.10	0.20	0.57
US/F	0.52	0.14	0.45
US/G	2.32	0.44	1.05
US/H	2.78	0.52	1.10
EP/E	0.57	0.10	0.65
EP/F	1.22	0.10	0.79
EP/G	0.51	0.06	0.33
EP/H	2.34	0.25	1.19
CN/E	3.40	0.45	1.14
CN/F	4.43	1.00	2.90
CN/G	3.09	0.15	0.33
CN/H	5.62	0.44	0.83
JP/E	0.05	1.00	1.43
JP/F	−0.82	0.26	0.42
JP/G	−0.24	1.00	1.17
JP/H	0.47	1.00	1.04
KR/E	2.39	0.04	0.23
KR/F	1.68	0.07	0.40
KR/G	3.87	0.51	2.15
KR/H	4.27	0.24	0.88

US/E represents technology portfolio E of the United States, similarly hereinafter

technologies had strong technological innovation capabilities; China focused on technology portfolios E and F to improve its technological innovation capabilities, increasing the R&D investment and enhancing the R&D efficiency of solar thermal technologies. Similar to the United States, the European Union also made efforts to promote the development of solar photovoltaic technologies, but mainly focusing on the technology portfolio H. In addition, it paid more attention on improving core technological capabilities, rather than the number of patents. In South Korea, the technology portfolio G saw a rapid development, which revealed its preference on R&D investment and innovation strategies. It is noteworthy that Japan experienced an extremely slow growth and even negative growth in terms of patent counts, which was mainly due to its long history of the development of solar energy technologies as well as the limitations of its innovative model. The relevant technologies were thus close to saturation in Japan, but it still cannot be underestimated considering a large number of patents.

Cluster analysis of scientific linkage and technological innovation capabilities

General comparisons

According to the above mentioned taxonomy, this study measures scientific linkage and technological innovation capabilities of the technology portfolios in the United States, the European Union, Japan, China and South Korea. In order to visualize the relation between scientific and technological innovation capabilities, the technological classes are positioned on the two-dimensional map based on the amount of knowledge exchanged with the solar energy technologies related patents, as proposed by Patel and Pavitt (1997). These two types of indicators are classified as follows: (1) in terms of scientific linkage, taking zero value as a criterion, TSCI itself has been standardized so that each technology portfolios can be classified as either science-based (namely high) or technology-based (namely low); (2) in terms of technological innovation capabilities, taking the mean value as a criterion, each class then can be classified as either high (above mean) or low (below mean) in another dimension. The detailed characteristics of knowledge flow patterns are described in the following section.

Firstly, technologies portfolios are classified based on the positioning of TSCI and RGR, as shown in Fig. 5. After calculating the mean value of RGR (1.78), the classes are then categorized into three groups, depending on the amount of knowledge flow: high TSCI-high RGR, high TSCI-low RGR and low TSCI-high RGR.

Secondly, technologies portfolios are classified based on the positioning of TSCI and RPP, as shown in Fig. 6. After calculating the mean value of RPP (0.40), the classes are then categorized into three groups, depending on the amount of knowledge flow: high TSCI-high RPP, high TSCI-low RPP and low TSCI-high RPP.

Finally, technologies portfolios are classified based on the positioning of TSCI and RTA, as shown in Fig. 7. After calculating the mean value of RTA (0.95), the classes are then categorized into three groups, depending on the amount of knowledge flow: high TSCI-high RTA, high TSCI-low RTA and low TSCI-high RTA.

After comparison and analysis, it is found that (1) technology portfolios H and G of the United States, which is mainly involved in solar photovoltaic technologies, are basically centralized at High TSCI-high RGR (or -high RPP or -high RTA); (2) technology portfolios that are of high TSCI-low RGR (or -low RPP or -low RTA) are gathered in the
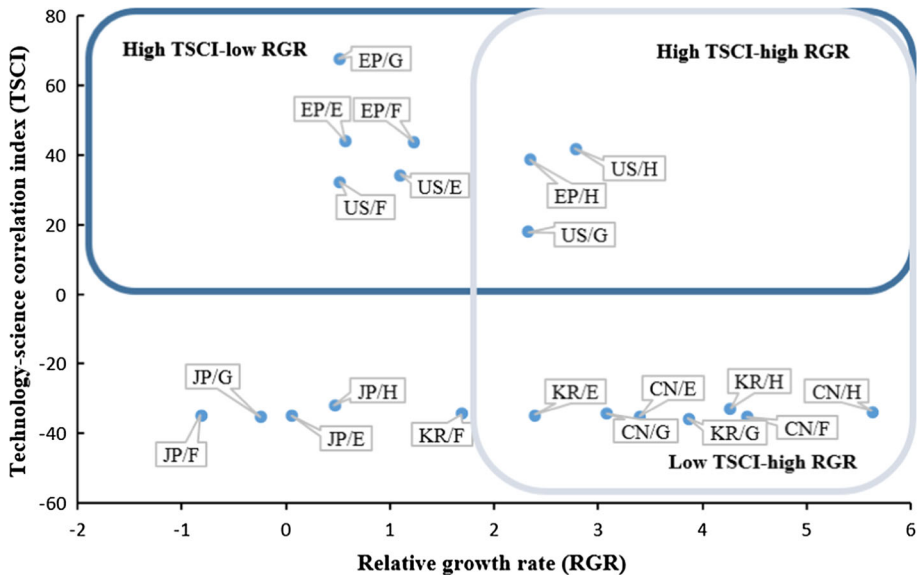
Fig. 5 Positioning of TSCI and RGR of technology portfolios in the United States, the European Union, Japan, China and South Korea, 1985–2014. *Source* EPO and compiled by the authors
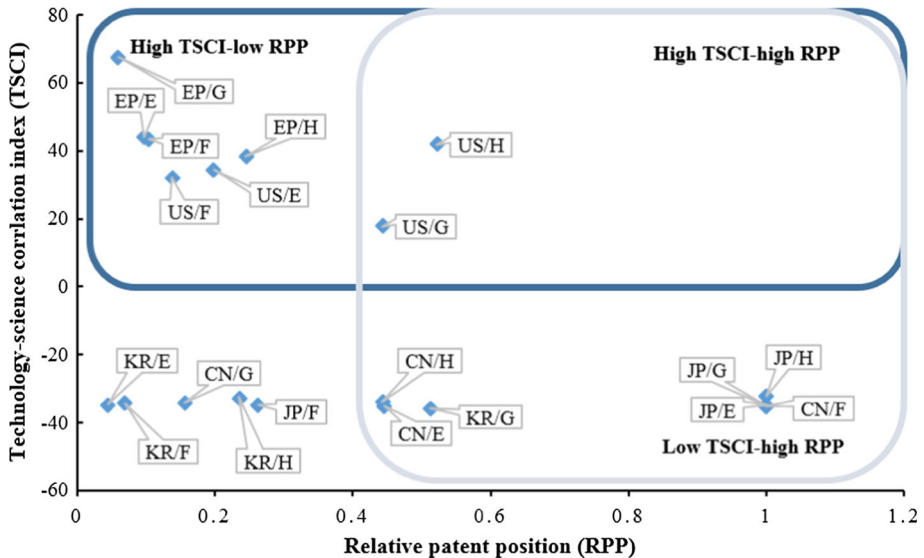

Fig. 6 Positioning of TSCI and RPP of technology portfolios in the United States, the European Union, Japan, China and South Korea, 1985–2014. *Source* EPO and compiled by the authors

United States and the European Union, reaching 10 and 6 respectively; (3) technology portfolios that are characterized with low TSCI-high RGR (or -high RPP or –high RTA) mainly belong to China, Japan and South Korea, reaching 9, 6 and 4 respectively.
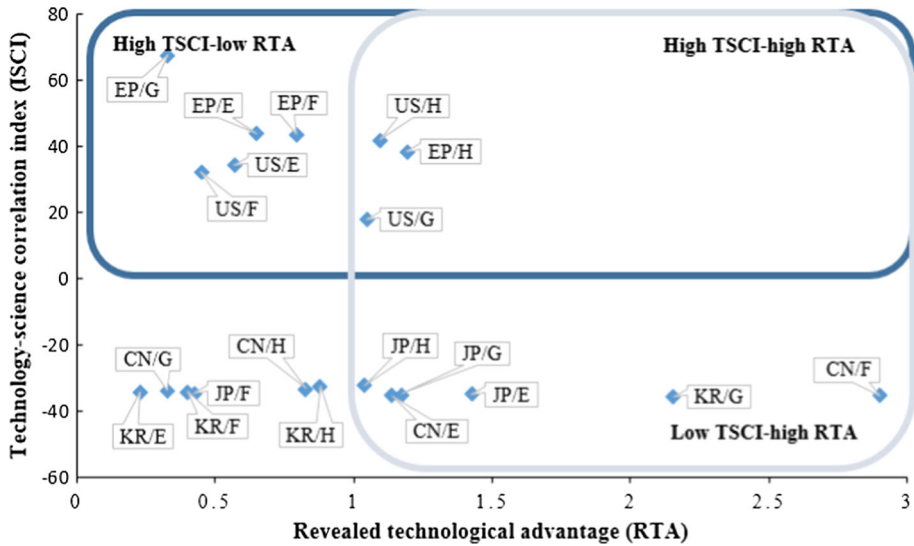
Fig. 7 Positioning of TSCI and RTA of the technology portfolios in the United States, the European Union, Japan, China and South Korea, 1985–2014. *Source* EPO and compiled by the authors

A comparison of technology portfolios

As shown in Fig. 8, the four-dimensional bubble chart is then employed to compare technology portfolio-level scientific linkage and technological innovation capabilities among these five countries and regions between 1985 and 2014. The X-axis in Fig. 8 represents relative growth rate (RGR), the Y-axis represents relative patent position (RPP), the Z-axis represents revealed technological advantage (RTA) indicated by the size of the bubble circles, and the U-axis represents technology-science correlation index (TSCI) indicated by the color of the bubble circles. Comparing and analyzing the bubble chart and Figs. 5, 6 and 7, it is not difficult to find that there exist significant differences in technological innovation characteristics among the United States, the European Union, Japan, China and South Korea.

In the United States and the European Union, solar industrial policies focused on science-based innovation, which means that there was a strong relationship between scientific research and industrial innovation. With relatively high scientific linkage, their technology portfolios H and G presented stronger technological innovation capabilities, while technology portfolios E and F did not show a stronger technological innovation capabilities. Technology portfolio H in the European Union presents were more likely to learn, absorb and apply knowledge from advanced fundamental researches at a high scientific relatedness. It is worth noting that its technology portfolio G was of a strong science relatedness, but the technological innovation capabilities was relatively weak, which was mainly due to its emphasis on patent quality rather than the number of patents.

But in Japan, solar industrial policies paid more attention to technology-based innovation, which means that there was not strong interaction between technology and scientific research in technology-based industry. As Japan's solar energy industry has entered a mature stage, based on more applied knowledge and existing technologies, technological innovation capabilities tended to reach a saturation state in the absence of external
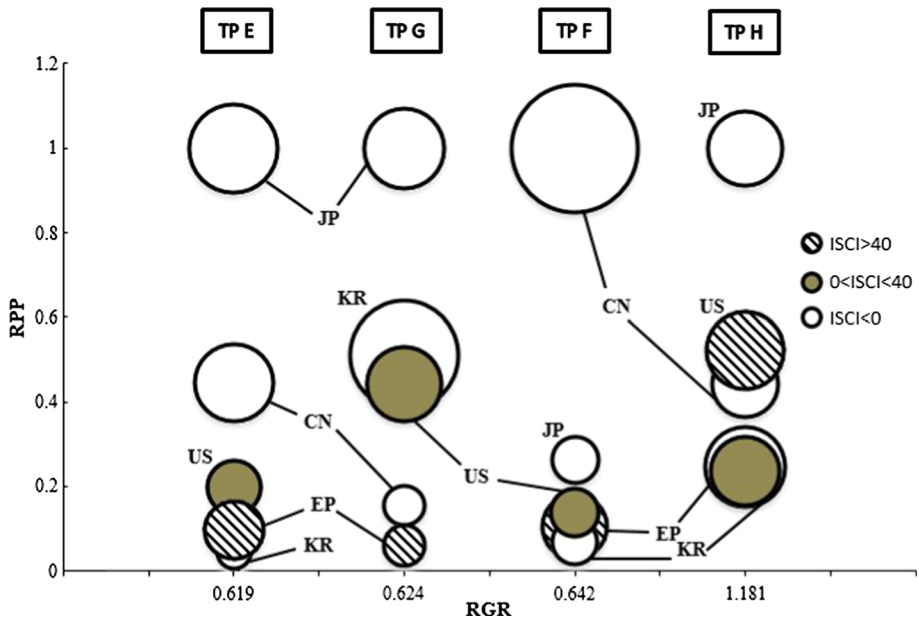
Fig. 8 Comparisons of scientific linkage and technological innovation capabilities of the technology portfolios in the United States, the European Union, Japan, China and South Korea, 1985–2014. *Note* the size of the bubble circles represents the magnitude of RTA. *Source* EPO and compiled by the authors

innovation such as new scientific discoveries. Despite of the large amount of patents, this trend slowed down and even showed negative growth in some technological fields. Whether Japan is able to sustain its competitive position in the technology portfolios G and H depends on when a breakthrough occurs, which rely largely on new scientific discoveries.

China and South Korea, as latecomers, focused on technology-based innovation due to its low input and high output in the solar energy industry so that reliance on scientific research was quite weak. With low scientific linkage, China's technology portfolios E and F had competitive advantages in technological innovation capabilities, while technological portfolios G and H showed relatively weak technological innovation capabilities. This indicates that China's technology portfolios G and H lacked support of scientific research. Compared with other countries and regions, South Korea's overall strength was weak, but its patenting performance in technology portfolio G was quite active.

Robustness checks

In order to ascertain the robustness of our findings, we performed several checks. We highlighted above that there are certain regularities between scientific linkage and technological innovation capabilities in the technological fields of solar thermal energy and photovoltaics. But the academic research plays different roles in technological innovation at each life cycle stage of a certain technology (Motohashi and Tomozawa 2014). Haupt

et al. (2007) indicate that literature citations increase only at the transition from intro-
duction to growth because at that early stage of a technology life cycle there is still much
fundamental (radical) new knowledge to cite which is published predominantly in scien-
tific literature. Hence, one may wonder whether our results are influenced by the effects of
life cycle activities. In order to separate and better control the effects of life cycle activities,
this paper would go more into details regarding the technological sub-fields of photo-
voltaics alone.

Currently, the photovoltaic field can be basically divided into three technological
generations, namely crystalline silicon, thin film[4] and organic compound.[5] As the corre-
spondence between IPC symbols and specific sub-fields is not always clear-cut, this paper
uses keywords to extract patent data of the technological sub-fields of photovoltaics, as
defined in Table 4.

Annual patents granted in the different sub-fields of photovoltaics is presented in Fig. 9.
It is a widespread approach to study technology life cycles by observing the evolution of
patent applications (e.g., Achilladelis et al. 1990; Achilladelis 1993; Andersen 1999).
Corresponding to product life cycles we can differentiate introduction, growth, maturity,
and decline as technology life cycle stages (Haupt et al. 2007). As can be seen from the
chart below, thin film and organic-based technologies at the growth stage saw a sustained
increase, while crystalline silicon-based technologies evolved into the phase of maturity
since the number of patent counts remains constant after 2000. Particularly, thin film
related patent applications experienced a marked rise, of which the relative growth rate
(RGR) reached 1.048. This dynamic added momentum to the whole photovoltaic field.

The three-dimensional color map is then employed to compare technological sub-field-
level scientific linkage and technological innovation capabilities among these five coun-
tries and regions between 1985 and 2014, as shown in Fig. 10. The X-axis represents
relative patent position (RPP), the Y-axis represents revealed technological advantage
(RTA), the Z-axis represents technology-science correlation index (TSCI) also indicated
by the color of the map surface. As can be seen from Fig. 10a, Chinese and Japanese
manufacturers fostered technology improvements of silicon-based cells, hoping to bring
system costs down much faster than anticipated and hinder innovative efforts for the
alternative approaches (as it became questionable if thin film and organic cells will still be
able to compete with silicon). This focus of Chinese manufacturers on the maturity tech
stage, driven by downstream technology improvements, led to the low science-based
values. Based on this innovation strategy, China showed relatively strong technological
innovation capabilities in silicon-based cells, but it is not surprising that China was unable
to outperform its competitors and find an advantageous niche in thin film or organic market
due to lack of corresponding basic research and cutting-edge science. But in Fig. 10b, c,
the United States and Europe concentrated on bringing novel science-based innovation into
the market, hopefully leapfrogging silicon-based technologies. Technically, the develop-
ment of thin film and organic cells at the growth tech stage demanded fundamental
(radical) new knowledge and upstream technological innovation. The science-based

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[4] Thin film technologies made out of a range of different semi-conductor materials, including amorphous
silicon, cadmium–telluride and copper indium gallium diselenide. While thin film technologies are less
efficient than silicon based cells, they are cheaper and more versatile than crystalline silicon based coun-
terparts (Timilsina et al. 2012).

[5] Organic compound solar cells are made by organic material, and dye-sensitized technology has emerged
recently as a special type of organic compound solar cell (Motohashi and Tomozawa 2014).

Table 4 Keywords to extract patent data of sub-fields in photovoltaics. *Source* Motohashi & Tomozawa (2014) and compiled by the authors

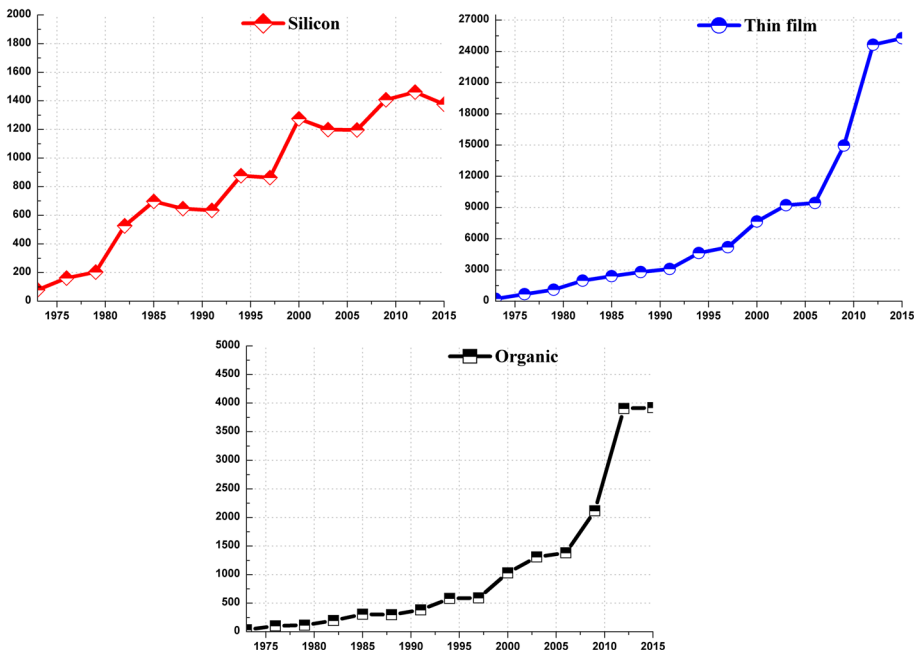| Technological field	Technological sub-field	Keywords
Photovoltaics (PV)	Crystalline silicon	Silicon, crystalline si, polycrystalline si
	Thin film	Thin film, a-si, amorphous, cds, cadmiumselenium, cigs, cdte, gaas, inp, cis, cuin, zns, cu2o, cus, agins, copper, in2o3, sns, mose2
	Organic compound	Organic, polymer, plastic, dye, titanium, oxide, tio2

Fig. 9 Annual patents granted in the different sub-fields of photovoltaics, 1973–2014. *Note* ending statistical decline is due to some patent applications published lagged. *Source* EPO and compiled by the authors

innovation led by the United States and Europe then promoted technological innovation of these two sub-fields as well as the major field of photovoltaics.

In terms of patent applications and technological innovation capabilities (especially in RGR), photovoltaics is currently dominated by thin film, a sub-field basically driven by science. Hence, we find no significant effect on our results, though the indicator, scientific linkage, varies to some extent in different technological generations.
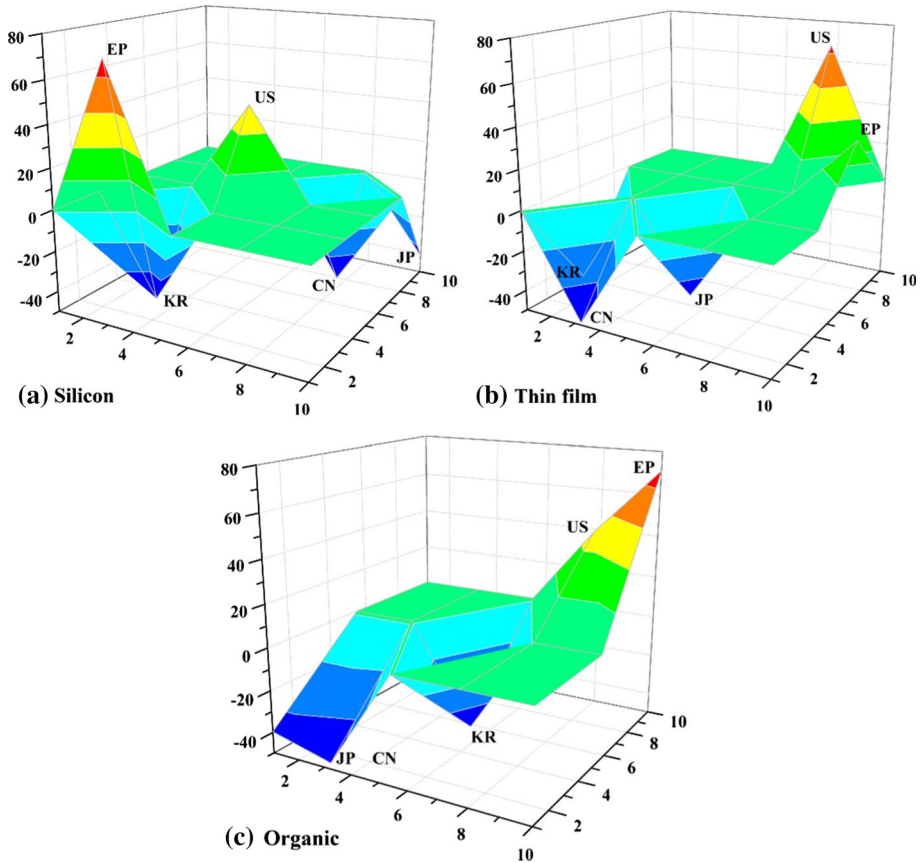
Fig. 10 Comparisons of scientific linkage and technological innovation capabilities of the sub-fields of photovoltaics in the United States, the European Union, Japan, China and South Korea, 1985–2014. *Note* the surface color represents the magnitude of TSCI. *Source* EPO and compiled by the authors

Conclusions and suggestions

Conclusions

From the perspective of science-based innovation, this study introduces measures of both scientific linkage [technology-science correlation index (TSCI)] and technological innovation capabilities [relative growth rate (RGR), relative patent position (RPP) and revealed technological advantage (RTA)] to compare and analyze the international competitiveness of solar energy technologies among the United States, the European Union, Japan, China and South Korea, based on the solar energy technologies-related patents in the European Patent Office (EPO) Worldwide Patent Statistical Database. From the above comparisons and discussions, we draw conclusions as follows:

Firstly, the various strategies adopted by these five countries and regions reflect their scientific linkage and innovation characteristics. In the United States and the European Union, solar industrial policies focused on science-based innovation, which means that there was a strong relationship between scientific research and industrial innovation. But in

Japan, China and South Korea, solar industrial policies paid more attention to technology-based innovation, which means that there was not strong interaction between technology and scientific research in technology-based industry.

Secondly, technological innovation capabilities are revealed in different countries and regions due to the scientific linkage of their solar energy industry. In the United States, technology portfolios H and G were characterized by the higher R&D scale and R&D efficiency, which means that its photovoltaic technologies had strong technological innovation capabilities. China focused on technology portfolios E and F to improve its technological innovation capabilities, increasing the R&D investment and enhancing the R&D efficiency of solar thermal technologies. In South Korea, the technology portfolio G saw a rapid development, which revealed its preference on R&D investment and innovation strategies. It is noteworthy that Japan experienced an extremely slow growth and even negative growth in terms of patent counts, which was mainly due to its long history of the development of solar energy technologies as well as the limitations of its innovative model.

Thirdly, solar photovoltaic technologies, especially thin film and organic cells, are progressed mainly by science-based innovation that involves the active participation of the science sector such as universities and public research intuitions, while solar thermal technologies are driven mainly by technology-based innovation, which are dominated by endogenous and accumulated technological progress. This is because technology portfolios H and G present strong technological innovation capabilities with high scientific linkage, but technology portfolios E and F are of strong technological innovation capabilities with low scientific linkage. In the light of the technological lift cycle, though the indicators varies to some extent in different technological generations, there is no significant effect on our results.

Suggestions

In the field of solar energy, the leading countries such as the United States have implemented different policies and measures to enhance their core competitiveness, many of which have a good guide and reference value, providing strategic opportunities for China, South Korea and other latecomer countries to catch up with and even overtake their counterparts if they gain a better understanding of science-based or technology-based innovation characteristics within the industry. Although technical guidance and support policies are necessary means in the early stage and commercialization stage of industrial development, it still rely on the cooperation of university-industry-government in the long term.

Firstly, to provide the necessary funding for the solar industry. As a science-based industry, compared with R&D investments on the information technology and bio-technology, the research and development of solar energy technologies usually requires a large sum of money and more importantly long-term investments. In fact, the development of a new energy technology may requires multibillion dollars and sustained investments for decades. This is because it is difficult for most countries to achieve this goal: in order to develop a new energy that is able to compete with traditional fossil fuels, what the solar energy industry urgently needs not only general process innovation but major technical breakthrough which is always in the wake of new scientific discoveries.

Secondly, the scientific research and development of solar photovoltaic technologies and solar thermal technologies should be provided with differentiated support and funding. Solar photovoltaic technologies are highly dependent on science-based innovation closely

with fundamental science, so that policy measures should focus on basic research to promote industrial development, supporting universities and public research institutions to carry on scientific research in the relevant fields and promoting new scientific discoveries. On the other hand, as solar thermal technologies is relatively insensitive to science-based innovation, the government should pay more attention on the research of generic technologies and applied technologies in the solar thermal fields, providing enterprises with subsidies and other preferential policies to leverage their R&D investment.

Thirdly, it is also necessary for governments to provide the impetus needed to promote the commercial application. The main problem is neither the speed of technological progress that restricts the development of solar energy nor a serious lack of cost advantage, but slow progress in commercial applications of advanced technologies. This means that government intervention in the commercial application stage is even more important than early intervention.

Appendix: Definitions for the solar energy technology related IPCs

Energy-related technology	International patent classification (IPC) symbols
Solar energy technology	F24 J 2/00, F24 J 2/02, F24 J 2/04, F24 J 2/05, F24 J 2/06, F24 J 2/07, F24 J 2/08, F24 J 2/10, F24 J 2/12, F24 J 2/13, F24 J 2/14, F24 J 2/15, F24 J 2/16, F24 J 2/18, F24 J 2/23, F24 J 2/24, F24 J 2/36, F24 J 2/38, F24 J 2/42, F24 J 2/46, F03G 6/06, G02B 5/10, H01L 31/052, E04D 13/18, H01L 31/04, H01L 31/042, H01L 31/18, E04D 1/30, G02F 1/136, G05F 1/67, H01L 25/00, H01L 31/00, H01L 31/048, H01L 33/00, H02 J 7/35, H02 N 6/00

Source WIPO. For definitions of IPC symbols, see www.wipo.int/classifications/ipc/en/

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